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title: **Hydrogeological characterisation of the heterogeneity of aquitards from a multilayered system**

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INTRODUCTION

In sedimentary basins, the vertical organization of geological deposits leads to the existence of interbedded aquifers and aquitards. This alternation of hydrogeological units forms a complex multilayered aquifer system. The aquitards, also called leaky confining layers are low permeability units generally composed of clay materials. They can have very high storage capacities but they cannot transmit water at rates fast enough to supply wells. Nevertheless, they can transmit water slowly from one aquifer to another leading to quality issues. This exchange is generally known as "leakage". This phenomenon can become very important for long-term transient systems and is generally considered as a significant component of the total inter-aquifer recharge. Then, it is necessary to assess these vertical fluxes as accurately as possible and integrate them in general groundwater flows in order to tackle the management of groundwater resources.

There is increasing evidence that flow through many aquitards is much more complex (Remenda 2001) than can be accounted for by simple one-dimensional vertical flow model (Eaton, 2007). This could be explained by multiple sedimentary layers of differing properties found in stratified rock sequences.

In order to quantify as accurately as possible the fluxes flowing through aquitards, the characterization of their architecture and their hydraulic properties remains a major objective.

BOREHOLE LOGGING CONTRIBUTION TO SPATIAL CHARACTERIZATION

Composed by sedimentary deposits that correspond to several transgressive-regressive episodes extending from Jurassic period (-210 ma) to the end of the Miocene (-5 Ma), the north part of the Aquitain sedimentary Basin shows a complex structure both vertically and horizontally. Therefore, this basin is a multilayered aquifer system (Figure 1) within which 6 main aquifers (one unconfined aquifer and five confined aquifers) are more or less connected and are separated by low-permeability units more or less continuous.

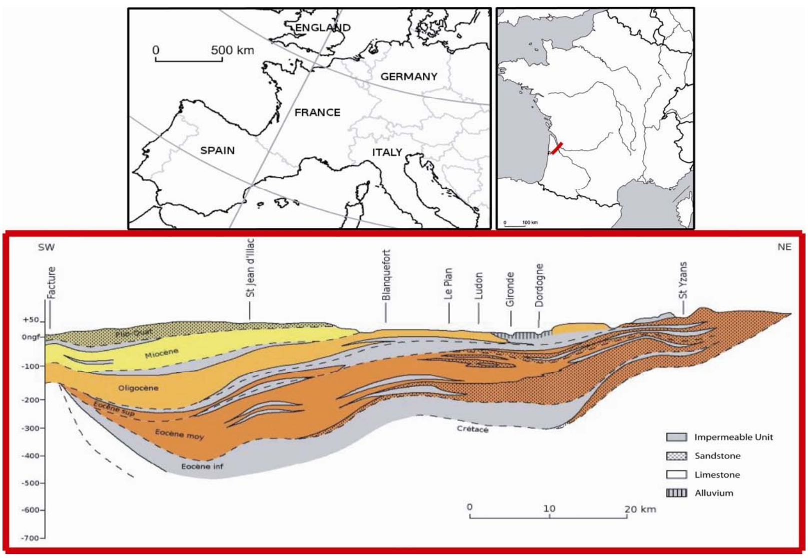


Figure 1. Schematic hydrogeological cross-section of the North of Aquitain Basin (Moussié, 1972).

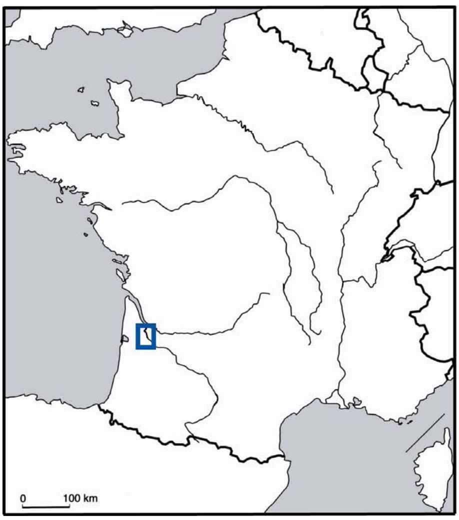
Currently, groundwater resources are broadly exploited for different uses (freshwater supply, geothermal energy, thermal water, agricultural and industrial domains…). The amount of water available from such system is an essential issue for the long-term management of freshwater supply. The anthropogenic influence manifests through important withdrawals concentrated on the three shallowest confined aquifers (Eocene, Oligocene and Miocene aquifers).

Two recent hydrogeological models developed in this area incorporate the confining layers. Even if they both identify the presence of vertical flows through the aquitards, they cannot correctly reproduce the functioning of the groundwater system and the level state of the water reserves. The lack of knowledge about aquitard structures and associated hydrodynamic measurements leads to those uncertainties. The use of direct or indirect measures to redefine the vertical organisation of the multilayered system and the horizontal heterogeneity of the aquitards appears to be a priority.

We present here borehole data that allow to re-examine the geological nature of the aquitards and their heterogeneities to increase the hydrogeological description of the multilayered aquifer system prior to its numerical implementation.

The measurements are based on the use of geophysical borehole loggings such as Gamma-ray, normal-resistivities and flowmeters which, used as a complement to geological data, allow to redefine facies boundaries with depth and to assess the heterogeneity of the aquitards.

A 110 wells database was constructed to organize information on well completion, geological data and geophysical loggings in the study area using Kingdom software (Fig. 2).



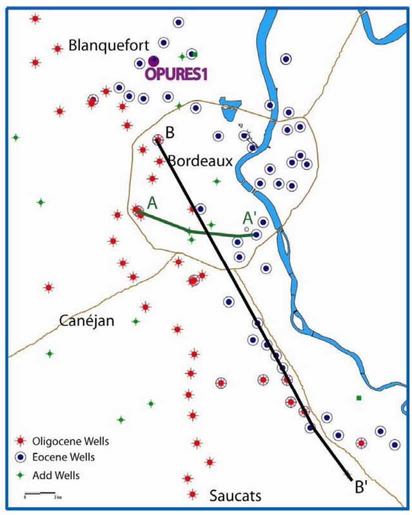


Figure 2. Map of the study area with boreholes and cross sections A-A' and B-B' locations.

Indeed, Gamma-ray logs allow to measure the total natural radioactivity of the formations crossed by a well. This measurement is essentially used to distinguish high radioactive shale beds, corresponding to aquitards in our case, from less radioactive sandstone and limestone. As for Normal-resistivity, it enables us to locate the main conducting and non-conducting formations (aquitards and aquifers). Flowmeter logs data were used to constrain more the reinterpretation by locating the permeable zones of aquifer's limits.

Before correlating all these geophysical loggings, Gamma-ray data were formatted for import. Indeed, the gamma-ray logs have been performed by different companies since the two last decades. Because of the use of different probes, scaled gamma-ray logs were produced from raw gamma-ray data to eliminate calibration gaps due to various probes. Gamma-ray data were scaled using the formula (Miller, 2000):

$$SCGR=\frac{(GR-Min)}{(Max-Min)}\times 100$$

Where *SCGR* is the percent of scaled gamma radiation, *GR* is the original gamma-ray value, *Max* is the base-line value for maximum radiation and *Min* is the base-line value for minimum gamma radiation.

The well-to-well correlations were constrained using the original geologic description to reduce the factors affecting the individual gamma-ray response such as logging speed, hole conditions effect (tubing, casing, cement, diameter…) (Serra, 2004).

HIGH RESOLUTION AQUITARD ASSESSMENT

In addition, a borehole called OPURES1 (Fig. 2 and 3) was drilled and completed for the first time in the region directly in an aquitard to observe on the long-term the evolution of the hydraulic gradient and perform in situ measurements to assess hydraulic parameters at different levels. It concerns the Oligocene/Upper Eocene Aquitard which is about 50 m thick.

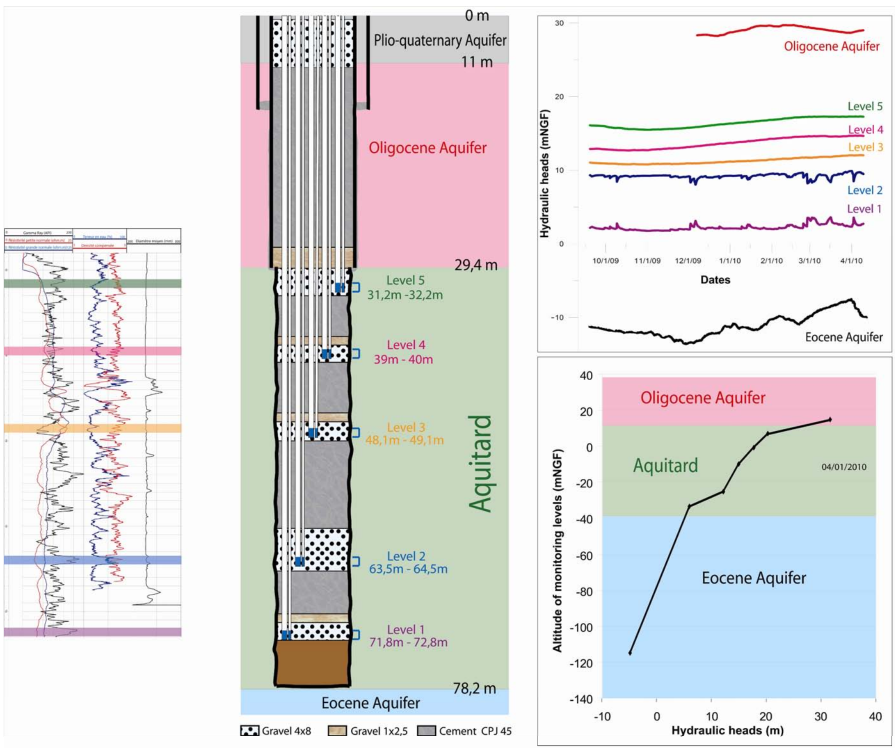


Figure 3. Completion of OPURES1 borehole and results.

It underlies the oligocene aquifer and confines the upper eocene and medium eocene aquifers. The latter is heavily pumped by a borehole which is 1km from our experimental site.

The borehole was drilled using both rock coring and air-rotary methods, logged using downhole geophysics, and instrumented as multi-level wells. Thus, 5 levels were selected for pressure monitoring inside the aquitards (Fig. 3).

Normal-resistivities and Gamma-ray logs as well as cores measurements confirm the heterogeneity of the aquitard. This is notably revealed by the presence of a silty clay layer. On a small scale, cores measurements showed some fractures and different indurated levels of generally small thicknesses. *In situ* hydrodynamic properties measurements are planned to account for this heterogeneity.

A non-linear hydraulic gradient is observed within the aquitard. This is likely due to contrasts of permeabilities. Actually, the hydraulic heads are not totally balanced. The aquifer exploitation can generate hydraulic disturbance which interferes in the balance.

DISCUSSION AND CONCLUSION

The use of borehole geophysical loggings shed new light on the geology of the Aquitain sedimentary basin in the region of Bordeaux (Fig. 4).

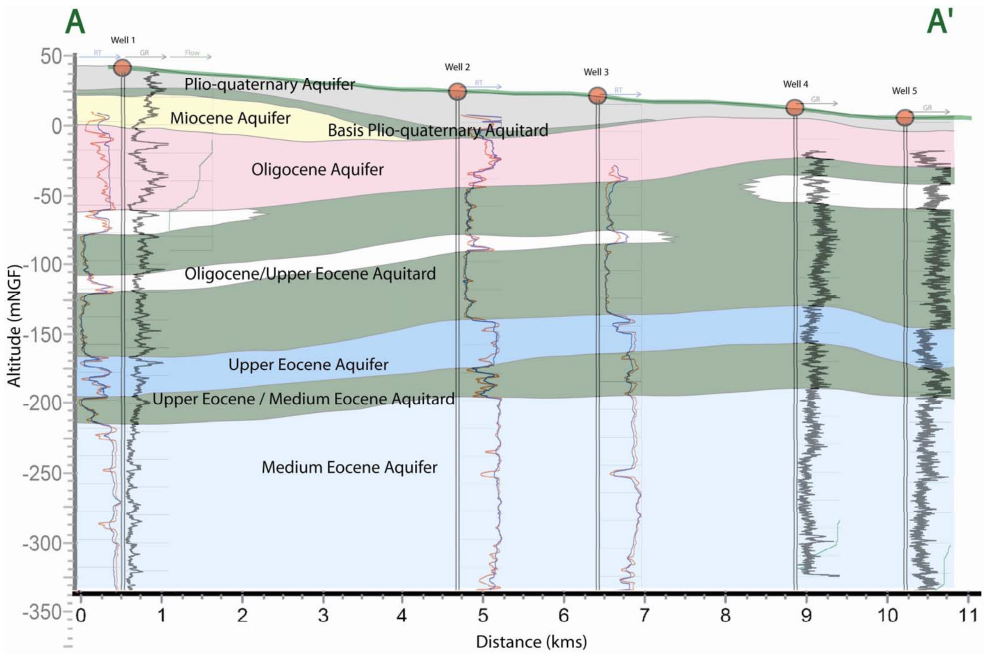


Figure 4. Example of interpretation from well logging data: RT= Normal-resistivity; GR= Gamma-Ray. Location of the cross section is indicated by the A-A' trace in Fig. 2.

By comparing two cross sections (Fig. 5), we can observe the contribution of borehole geophysical loggings to the reconstruction of the geology and an accurate 3D model.

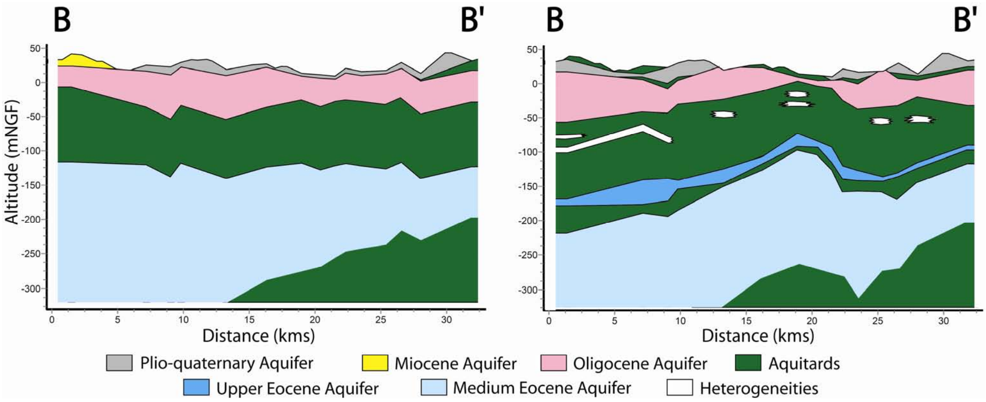


Figure 5. Comparison of two cross sections. One based on geological data, the other one constrained by the use of borehole geological loggings. Location of the cross section is indicated by the B-B' trace in Figure 2.

The comparison reveals the presence or not of clayey layers which were not integrated in the generally accepted geological model. The first one is situated under unconfined aquifer. This aquitard will limit the recharge of underlying aquifers and will protect them from pollution. We also noticed that a new aquifer body (Upper Eocene) appeared on the borehole geophysical loggings. The medium Eocene is thus divided into two aquifers (Upper Eocene and Medium Eocene) separated by an aquitard. The Upper Eocene is currently not used for the freshwater supply. Next, in some areas, the thin aquitard which separate the Miocene and the Oligocene does not exist leading to the possibility of hydraulic continuity. Finally, heterogeneities within the aquitards were pointed out. These heterogeneities correspond to limestone and sandstone with more or less clay. They form lenses of limited extension at different levels within the aquitard.

Finally, this reinterpretation allowed to assess the geological nature of rocks composing the aquitards in order to provide relative information on permeability values related to each facies.

The integration of geological and hydrogeological properties of aquitards in the numerical models allows to quantify the impact of local heterogeneity on groundwater flows. The results yield to the update of the regional model which will allow to assess an accurate description of leaky fluxes from the aquitards in the scope of enhancing freshwater exploitation.

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